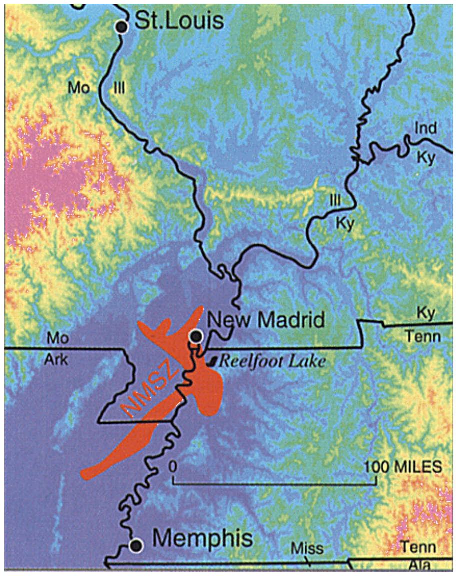
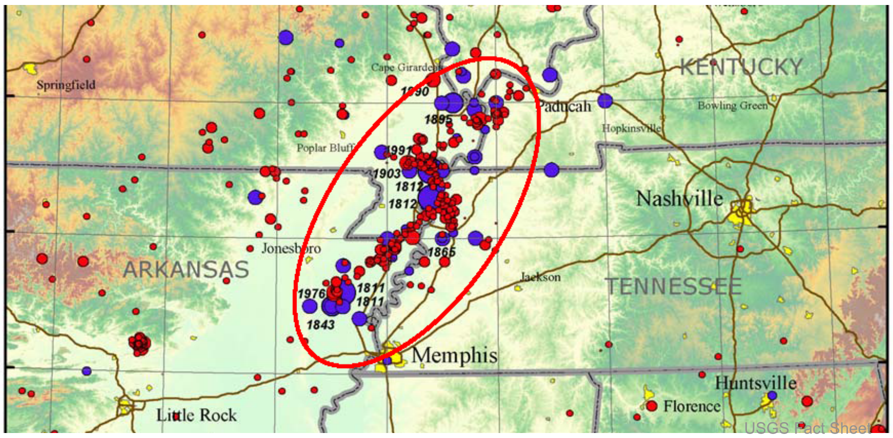
The New Madrid Seismic Zone



Motivations

- High hazard and risk to eight states and several cities in a relatively unprepared region
- Very large uncertainties in all aspects of the intraplate earthquake source model and seismic hazard assessment
- Repeated clustering of large-magnitude earthquakes
- Controversy over implications of low measured strain rates
- Upcoming bicentennial activities, conferences, and National Level Exercise (NLE 2011)

New Madrid Seismic Zone

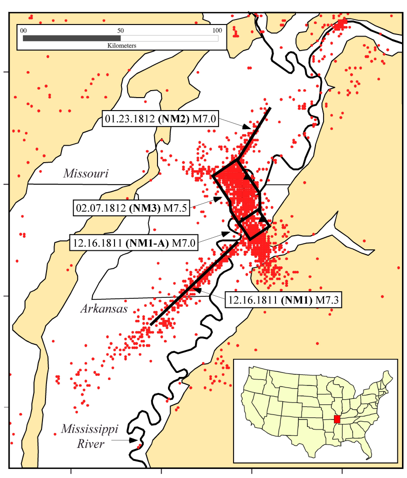


- Most seismically active area east of Rocky Mountains
- Produces 200 earthquake annually in M 1.5-4 range
- Largest instrumetally recorded event M 5 near Marked Tree, AR in 1976

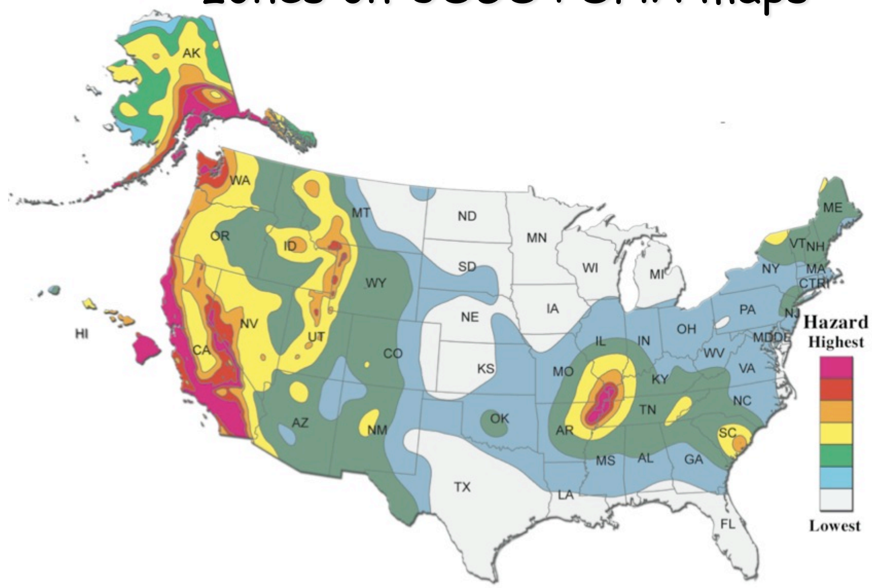
1811-1812: The New Madrid Sequence

Four M>7.0 earthquakes:

Dec. 16, 1811 (2:15 AM)
Dec. 16, 1811 ('dawn')
Jan. 23, 1812 (9:00 AM)
Feb. 7, 1812 (3:45 AM)



NMSZ is one of the "highest hazard" zones on USGS PSHA maps



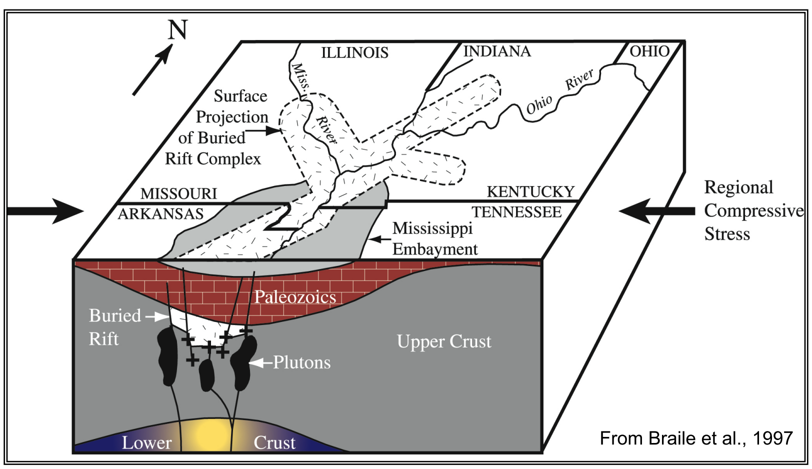
USGS Probabilities of Large New Madrid Earthquakes in Next 50 Years

Magnitude ~ 7.5-8.0
(similar to 1811-1812 earthquakes)
- Approximately 7-10%

Magnitude 6.0 or greater
(such as the 1843 Marked Tree, AR
and 1895 Charleston, MO earthquakes)
- Approximately 25-40%

Tectonic setting and prehistoric earthquake record

Geologic-Tectonic Setting

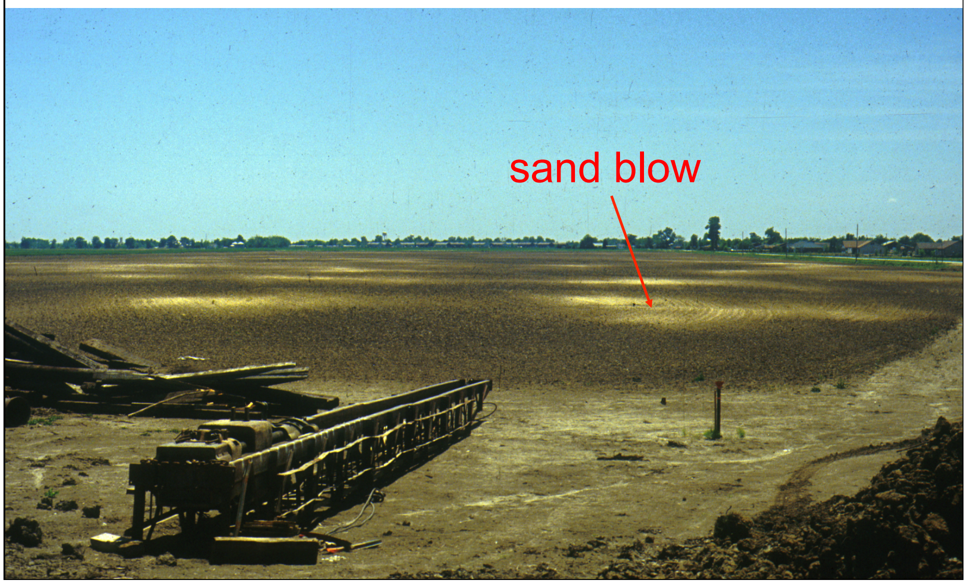


From Braile et al., 1997

- New Madrid region underlain by Reelfoot Rift
- NM earthquakes result of reactivation of ancient rift faults

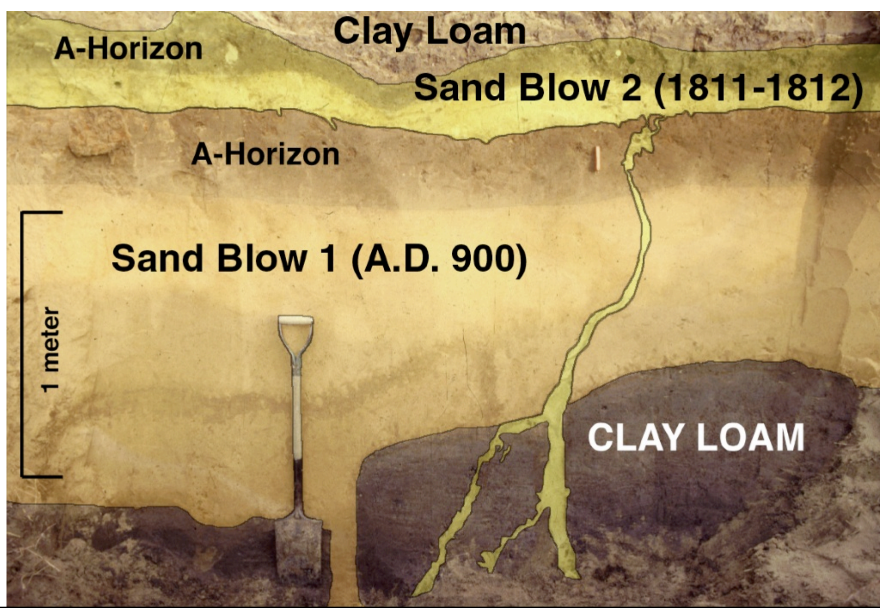
New Madrid Sand Blows

Blytheville, Arkansas

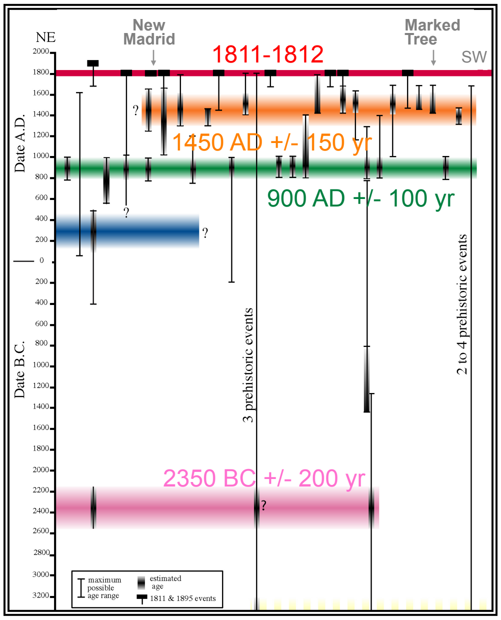


Smoking Gun of Large Past Earthquakes

Southeast Missouri

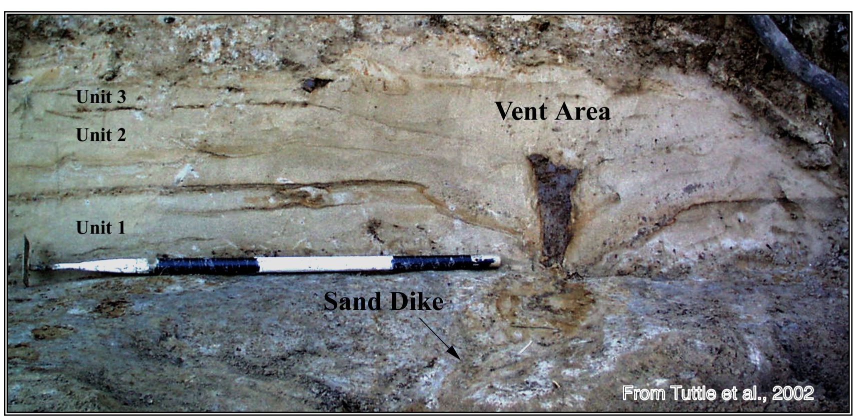


NM Paleoearthquake Chronology



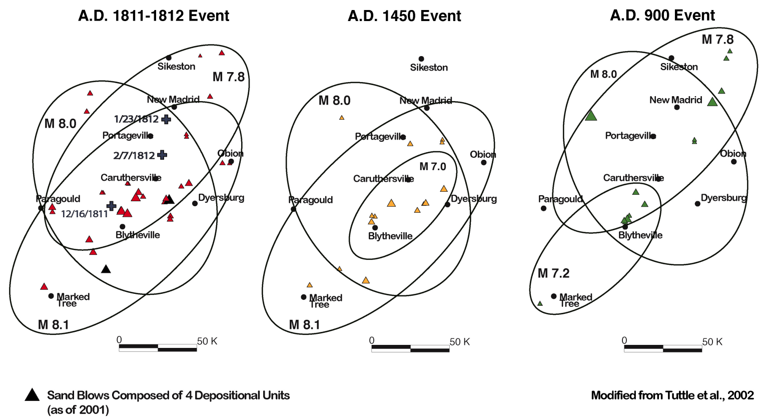
- Well-constrained ages estimates for numerous sand blows
- Age estimates cluster at 1450 AD, 900 AD and 2350 BC - timing of past events
- Suggestion of other events - 300 AD and 1100 BC
- Estimate of average recurrence interval of 500 years is based on only 2 earthquake cycles
- Chronology is incomplete temporally and geographically but could be improved

Evidence for Clustered Earthquakes



- Saucier (1989) observed historic sand blows composed of several depositional units related to 3 largest eqs in 1811-1812 sequence
- Sand layers separated by clayey silt - short periods of quiescence between eqs
- Prehistoric sand blows are *large, compound, and broadly distributed* like historic features
- They likely formed during previous New Madrid events, not multiple smaller eqs

Clustered Earthquakes



- Bi-modal clustering; intracluster times - days to months; intercluster times - 300 to 800 yr (1700 yr)
- Temporal clustering may result from contagion and complex interaction between faults

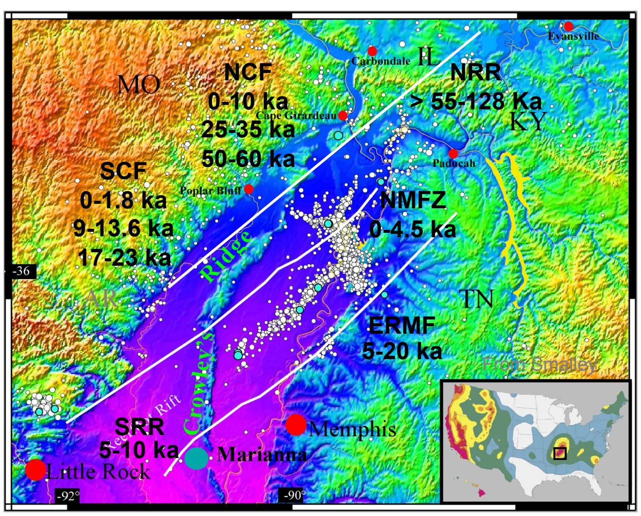
NM Paleoearthquake Chronology

- Earlier sequences possibly involved Bootheel Lineament (Guccione et al., 2002)
- Supporting evidence: deformation along Reelfoot & Bootheel faults, at Reelfoot & Big Lakes (Kelson et al., 1996; Guccione et al., 2002, 2005), and straightening events of Mississippi River channel northeast of Reelfoot fault (Holbrooke et al., 2006)

… we now know:

- New Madrid Seismic Zone produced large quakes in 1811-12, ~1450 AD, ~900 AD, and ~2350 BC
- The average time between these events is about 500 years at least during past 1200 years
- The prehistoric earthquakes were similar in size to 1811-1812 earthquakes
- Each New Madrid event was a sequence of earthquakes, including multiple very large mainshocks, much like the 1811-1812 sequence

Paleoseismology of Reelfoot Rift



Seismicity migrates (5-15 ky) within RR fault system; NMFZ - New Madrid fault zone, ERMF - E Reelfoot Margin flt, CF - Commerce flt

Earthquake magnitudes?

Big, but How Big?

1973: 7.0 – 7.3 (Nuttli)

1979: 8.75 (Nuttli*)

1996: 7.8 – 8.1 (Johnston)

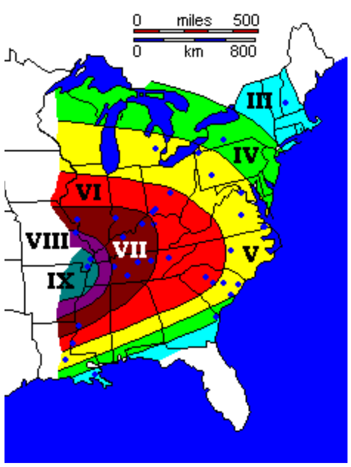
2000: 7.0 – 7.5 (Hough)

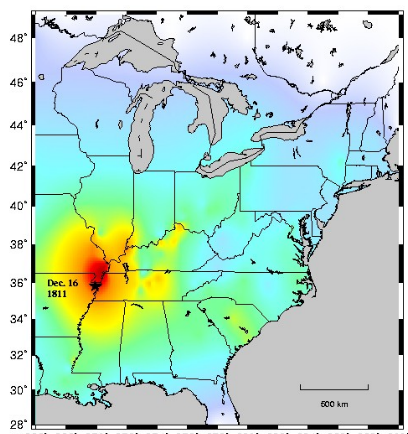
2004: 7.5 – 7.8 (Bakun)

Magnitude Uncertainties

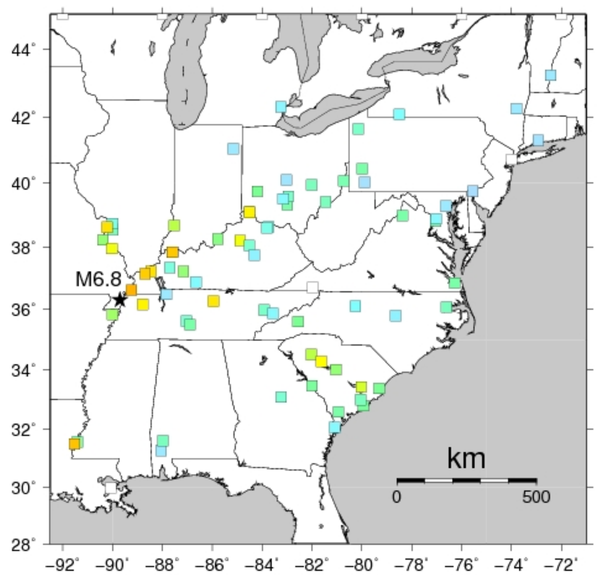
- Formal uncertainties (Bakun and Wentworth, 1997)
- Intensity values
- Attenuation model:
  1) appropriate for region?
  2) appropriate for large magnitudes?
- Location

Intensity Assignments





Consensus Intensities



Conclusions: Consensus View

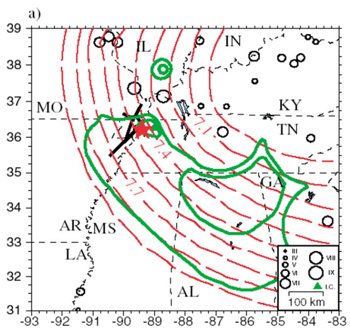
"Model 1"

- 12/16/1811: 6.8
- 12/16/1811: 6.7
- 1/23/1812: 6.8
- 1/23/1812: 6.5
- 2/7/1812: 7.3

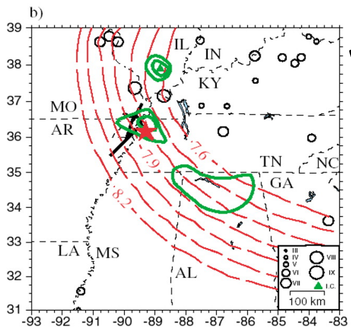
"Model 3"

- 12/16/1811: 7.0
- 12/16/1811 (a/s): 6.9
- 1/23/1812: 7.0
- 1/23/1812: 6.7
- 2/7/1812: 7.6

Improving the magnitude estimates
vs
Improving the uncertainty estimates



"Model 1" (Bakun et al., 2003):
M_I=7.4 (7.0-8.1)

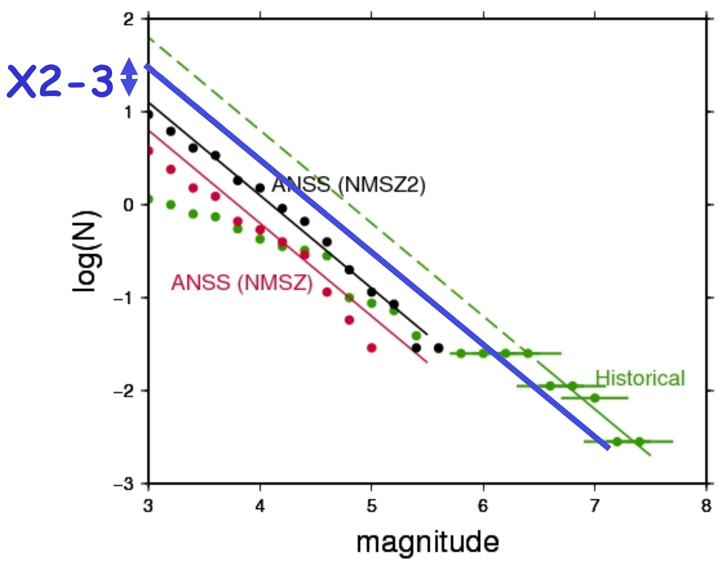


"Model 3" (Bakun and Hopper, 2004):
M_I=7.8 (7.4-8.1)

"Preferred solution"
M_I=7.8 (7.4-8.1)

Long-term Magnitude Distribution?

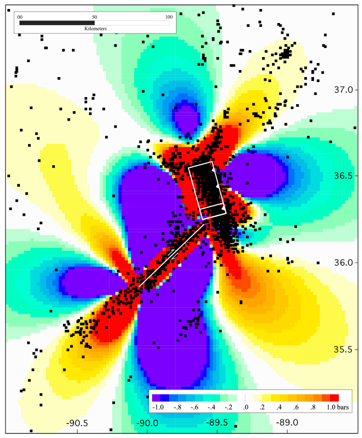
Magnitude Uncertainties



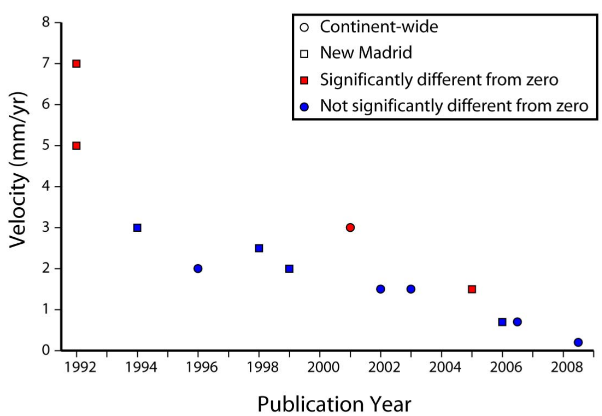
Observed strain rate?

Breaking News

- Background seismicity = continuing aftershocks, therefore no hazard (Nature, 11/5/2009)?



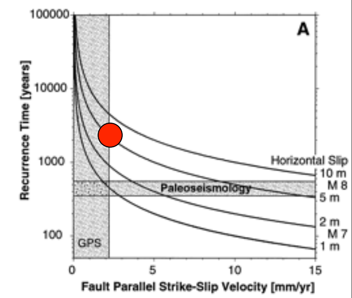
GPS Constraints:

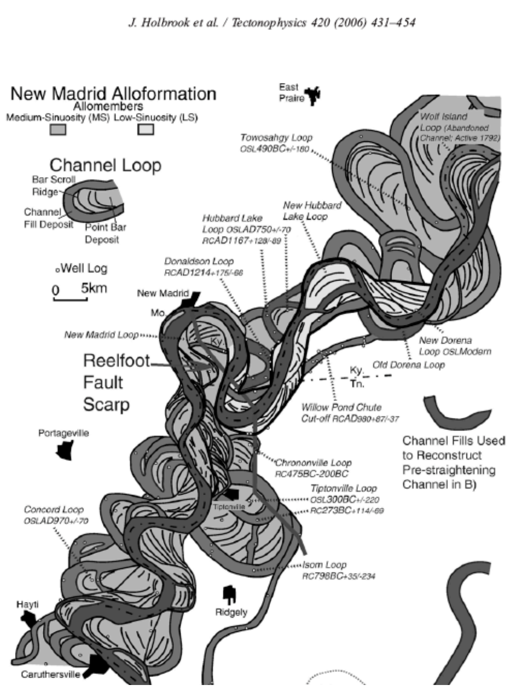


"At plate boundary faults, a balance is achieved over <1000 years between the rates at which strain accumulates and is released in large earthquakes. Whether this steady-state model, which forms the basis for seismic hazard estimation, applies to continental plate interiors, where large earthquakes are infrequent, is unresolved." *From Calais & Stein, Science, "Time-variable deformation in the New Madrid Seismic Zone, 2009.*

Viable Seismicity Models

- Characteristic earthquake model
- Gutenberg-Richter distribution:
  - *b*-value = 1
  - *a*-value underestimated by catalog
  - ETAS clustering statistics
  - 1 M8/2500 years
  - Mmax = low Mw7



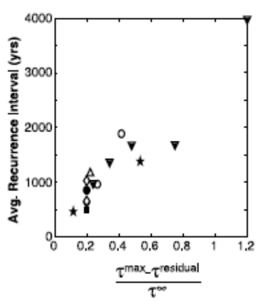


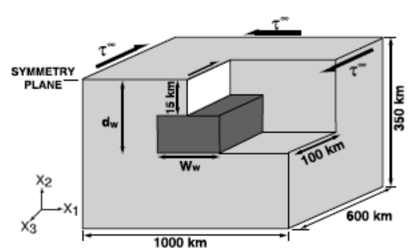
There's more to the story than GPS can tell us.

The straightening responses initiated at 2244 BC to 1620 BC and 900 AD, respectively, and each records initiation of a period of Reelfoot fault slip after millenia of relative tectonic quiescence. *From Stratigraphic evidence for millenial-scale temporal clustering of earthquakes on a continental-interior fault: Holocene Mississippi River floodplain deposits, New Madrid seismic zone, USA*

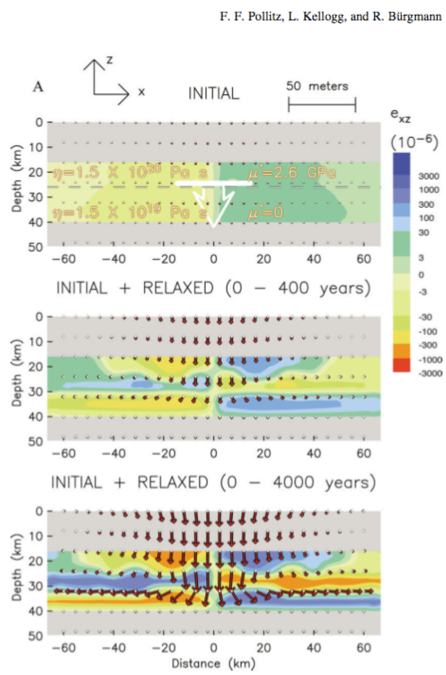
Models for repeated generation of large NMSZ earthquakes – consistent with low strain rate?

There are models that satisfy ALL the observations.





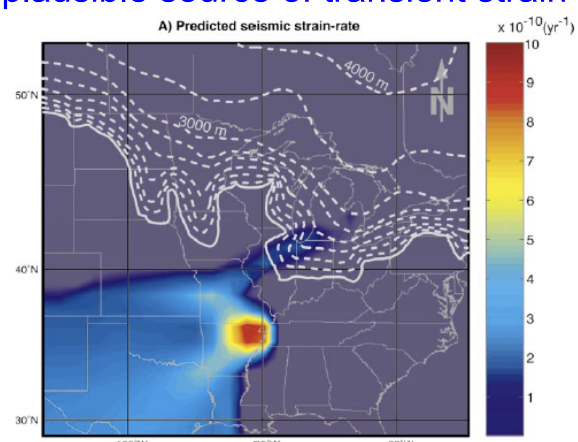
We present a time-dependent model for the generation of repeated intraplate earthquakes that incorporates a weak lower crustal zone within an elastic lithosphere. … Computed interseismic strain rates may not be detectable with available geodetic data, implying that low observed rates of strain accumulation cannot be used to rule out future damaging earthquakes.
From Kenner & Segall, Science, A mechanical model for intraplate earthquakes: application to the New Madrid seismic zone, 2000.



Other models for Stress Concentration

Following Stuart *et al.* (1997), we postulate an active role for the relatively dense rift pillow in concentrating stress in the NMSZ.
This model is a variation on that presented by Grana and Richardson (1996). it implies essentially constant and extremely low deformation rates. The new model is capable of producing a sequence of earthquakes such as those which have occurred within the past few thousand years (Van Arsdale, 2000), and it is contingent only upon recent weakening of the lower crust. *From "Sinking Mafic Body in a Reactivated Lower Crust: A Mechanism for Stress Concentration at the New Madrid Seismic Zone"*

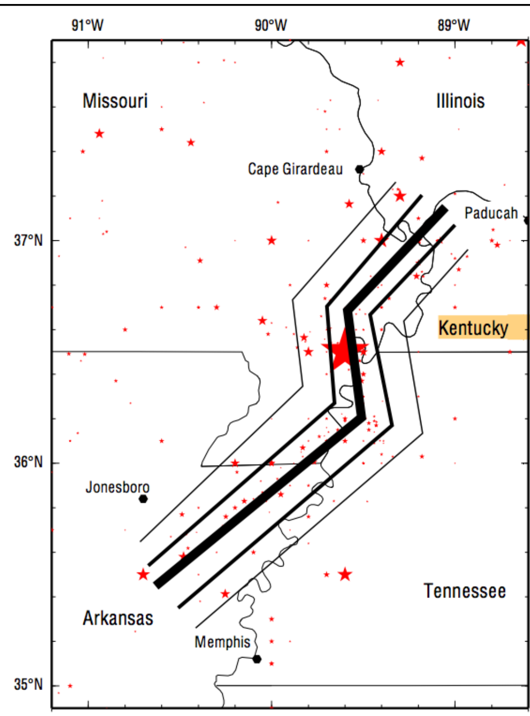
Another plausible source of transient strain localization…

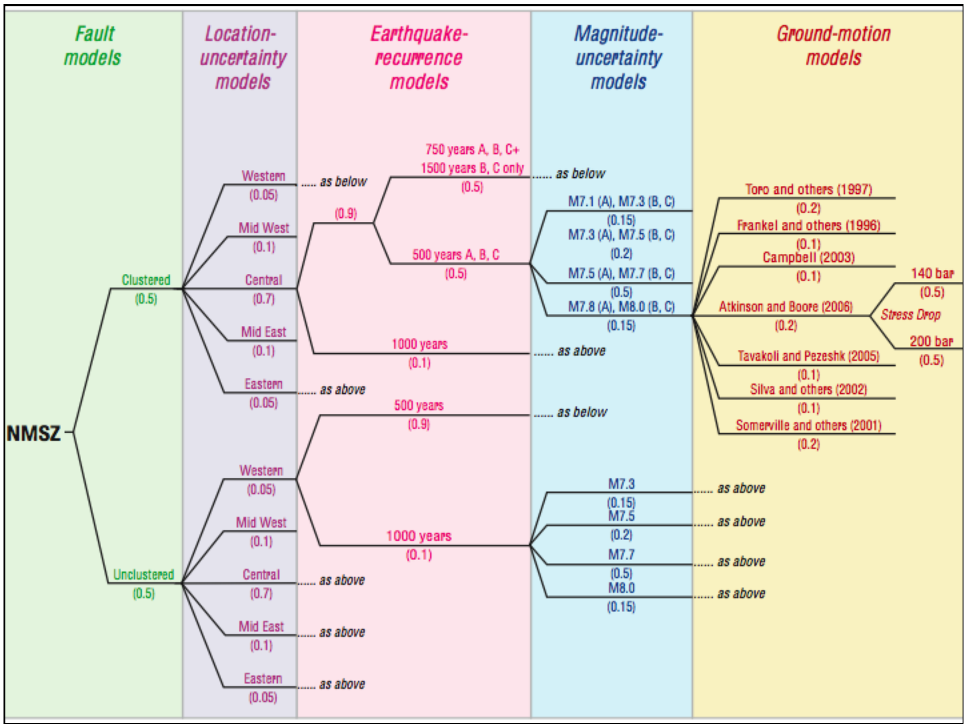


The removal of the Laurentide ice sheet that covered large parts of the northern United States until ca. 20 ka changed the stress field in the vicinity of New Madrid and caused seismic strain rates to increase by about three orders of magnitude. The modeling predicts that the high rate of seismic energy release observed during late Holocene time is likely to remain essentially unchanged for the next few thousand years.
From Grollimund & Zoback, Geology, Did deglaciation trigger intraplate seismicity in the New Madrid seismic zone?, 2001.

So what is the level of hazard?

USGS source model for NMSZ





Key questions

- Magnitude of historic and prehistoric earthquakes
- Intensity distribution of past NMSZ earthquakes
- Recurrence interval of NMSZ earthquakes
- Nature of the fault loading/unloading process
- Whether the same faults re-rupture
- Whether a characteristic or G-R model applies
- What should be inferred from low observed strain rates
- Whether NMSZ events always occur in clusters
- Whether a M7 event in the NMSZ will be followed by others
- Whether the USGS National Seismic Hazard Maps properly characterize NMSZ sources